

DARK MATTER IN THE LIGHT OF COBE*

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The observations of all three *COBE* instruments are examined for the effects of dark matter. The anisotropy measured by the DMR, and especially the degree-scale ground- and balloon-based experiments, is only compatible with large-scale structure formation by gravity if the Universe is dominated by non-baryonic dark matter. The FIRAS instrument measures the total power radiated by cold dust, and thus places tight limits on the absorption of starlight by very cold gas and dust in the outer Milky Way. The DIRBE instrument measures the infrared background, and will place tight limits on the emission by low mass stars in the Galactic halo.

1. Introduction

While *COBE* (Boggess *et al.* 1992) has no instruments that directly detect dark matter, its three instruments offer important clues about the baryonic and non-baryonic content of the Universe. The FIRAS observations of the spectrum of the cosmic microwave background radiation (CMBR) show that any deviation from a blackbody are very small (Mather *et al.* 1990 and Mather *et al.* 1994). This limits the possible effect of energetic explosions on the formation of large-scale structure (Wright *et al.* 1994). If gravity is the force responsible for large-scale structure, then the DMR observations of anisotropy require a non-baryonic dark matter dominated Universe. Even the baryons in the Universe are mostly in a dark form, but FIRAS observations of the millimeter emission from the Galaxy show that these dark baryons can not be in clouds of very cold gas and dust associated with the CO absorbing clouds seen by Lequeux *et al.* (1993). However, even more compact configurations of baryons are allowed: brown dwarfs. A Galactic halo of old cold brown dwarfs will be essentially undetectable by the DIRBE instrument unless all of the mass is in objects right at the limit of hydrogen burning.

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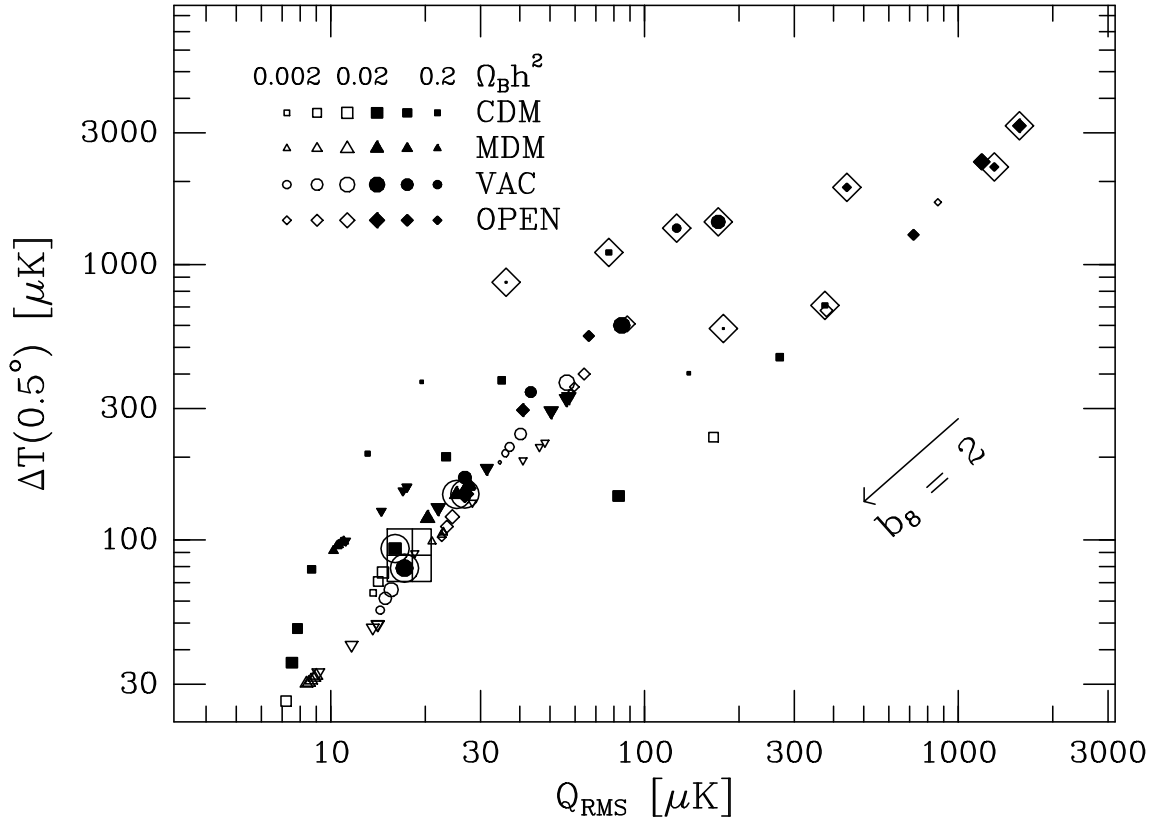


Fig. 1.— Predicted ΔT for Holtzman models at 0.5° scale *vs.* quadrupole scale.

2. DMR ΔT and non-Baryonic Dark Matter

The DMR anisotropy implies a small level of gravitational potential perturbations via the Sachs-Wolfe (1967) effect. At the same time, models of large-scale structure formation require certain levels of gravitational forces which can be converted into predicted ΔT 's. Figure 1 shows the predictions from the models of Holtzman (1989) compared to the *COBE* DMR $\langle Q_{RMS}^2 \rangle^{0.5}$ and the anisotropy at 0.5° measured by the MAX experiment (Clapp *et al.* 1994 and Devlin *et al.* 1994). The models with only baryonic matter are surrounded by open diamonds, while models emphasized by Wright *et al.* (1992) are surrounded by open circles. The CDM+baryon model and the vacuum dominated model (which still has 90% of the matter non-baryonic) both sit on top of the observed ΔT 's, while the open model and the mixed dark matter model need bias factors $b_8 < 2$ to agree with the data. The nearest baryonic model needs $b_8 \approx 10$ to fit the data, which is not reasonable. This problem with baryonic models arises because non-baryonic dark matter perturbations start to grow at $z_{eq} \approx 6000$, while baryonic perturbations can only start to grow at $z_{rec} \approx 10^3$, and thus lose a factor of $\gtrsim 6$ in growth.

8-14 /cm Flux in Microergs/cm^2/sr

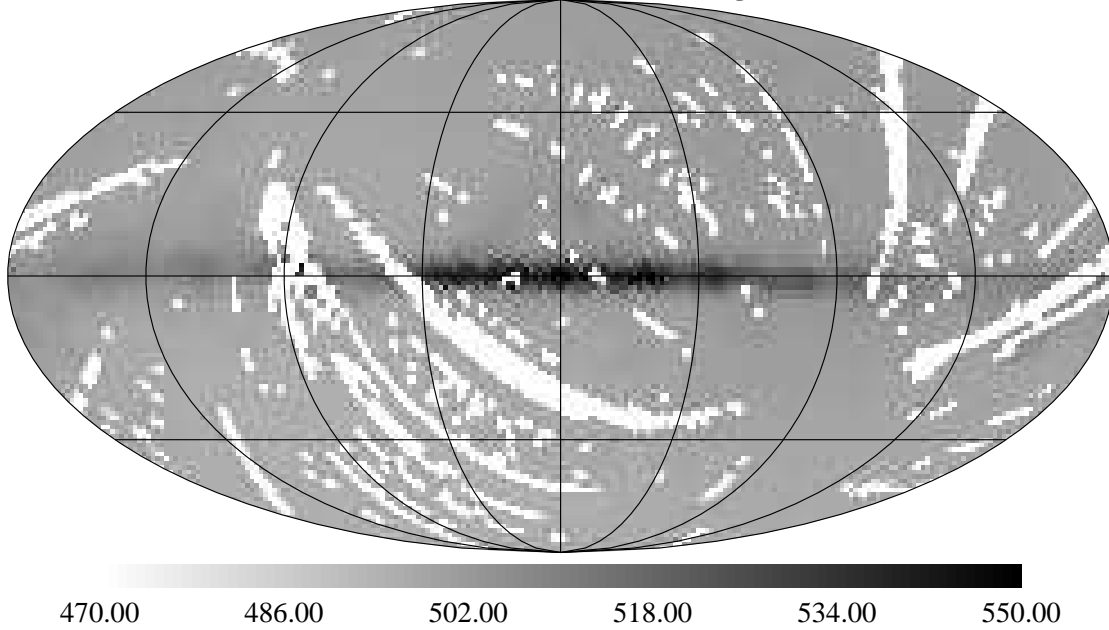


Fig. 2.— The total FIRAS flux in the 8-14/cm band.

3. FIRAS Limits on Very Cold Dust

Lequeux *et al.* (1993) have observed CO absorption toward extragalactic radio sources at low galactic latitudes. In at least one case the CO emission is very low, indicating very cold gas with $T_{ex} = 3.5$ K. Since most surveys for interstellar material are based on measuring emission, there is the possibility that a large amount of very cold gas and dust could be hidden in cold clouds. But any starlight absorbed by these clouds will be reradiated in the millimeter region where the FIRAS instrument on *COBE* is sensitive. FIRAS uses bolometers which are approximately equally sensitive at all wavelengths, so the limit placed on the absorption of starlight by the cold clouds is roughly independent of their temperatures. Because of the measured $T_{ex} = 3.5$ K, I have chosen the band $8 - 14 \text{ cm}^{-1}$ which corresponds to $h\nu/kT_{ex} = 3.3$ to 5.8 , which should include a fraction

$$\frac{\int_8^{14} \nu^\beta [B_\nu(T_d) - B_\nu(T_\odot)] d\nu}{\int_0^\infty \nu^\beta [B_\nu(T_d) - B_\nu(T_\odot)] d\nu} \approx 0.5 \quad (1)$$

of the power power emitted by the very cold dust grains with emissivities varying like ν^β for $\beta \approx 1.5$ and dust temperature $T_d = 3.5$ K.

Lequeux *et al.* observe 4 clouds on a total path length $\sum \csc |b| = 66$. Thus the optical depth from pole to pole of the disk is $\tau = 2 \times 4/66 = 0.12$. This implies that a

8-14 /cm Residual in Microergs/cm^2/sr

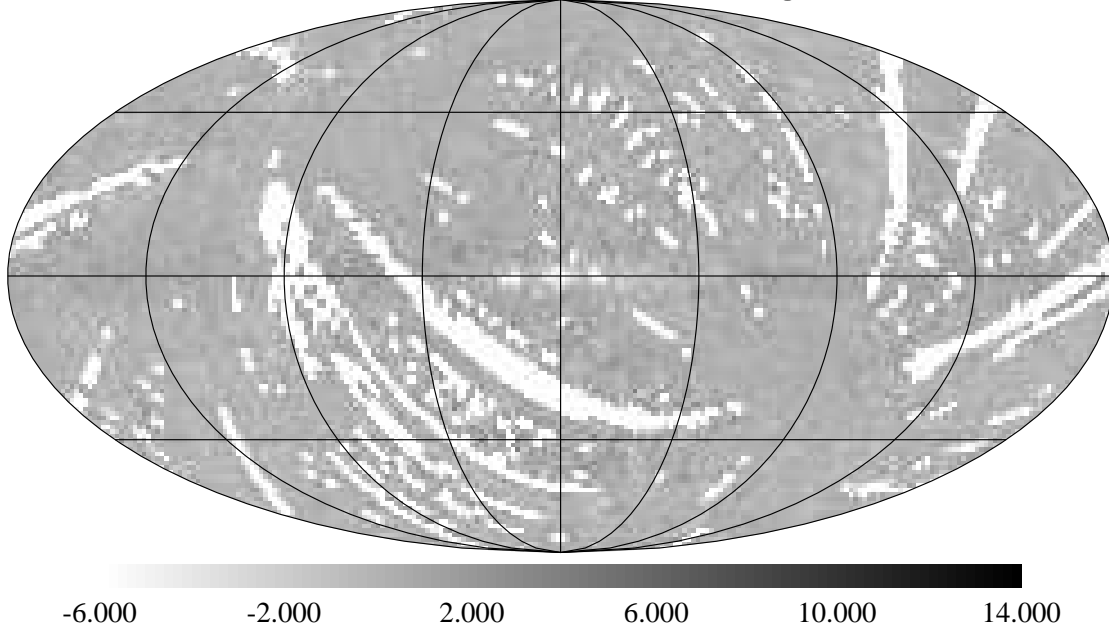


Fig. 3.— The residual FIRAS flux after subtracting the monopole and dipole and fitting for Galactic dust.

plane-parallel galactic disk in an isotropic optical background J will absorb a power per unit area of

$$\begin{aligned} P &= J \int \sin |b| (1 - \exp(-\tau \csc |b|)) \cos b db dl \\ &= 4\pi J \int_0^1 \mu (1 - \exp(-\tau/\mu)) d\mu = 1.24J. \end{aligned} \quad (2)$$

Considering only the part of the sky with $\sin |b| < 0.1$, I expect that the flux per radian of Galactic plane observed by FIRAS will be approximately

$$F = \frac{P \ln(s_{max}/s_{min})}{4\pi} \quad (3)$$

where the maximum distance along the line-of-sight s_{max} can be taken as the exponential scale length of the disk, or about 3 kpc, while the minimum distance s_{min} can be taken to be 10 times the scale height of the disk or about 1 kpc. Thus the very cold dust should radiate about $0.05J$ W/m²/rad into the 8-14 cm⁻¹ band.

The mean excess emission in the 8-14 cm⁻¹ band over the model

$$I_\nu(l, b) = B_\nu(T_o + D_x \cos l \cos b + D_y \sin l \cos b + D_z \sin b) + g(\nu)G(l, b) \quad (4)$$

in the region with $\sin |b| < 0.1$ and $\cos l < 0.866$ is 6×10^{-10} W/m²/sr, where T_\circ is the mean temperature of the cosmic background, D_i are the components of the dipole anisotropy, $g(\nu)$ is the average galactic dust spectrum, and $G(l, b)$ is the dust map (Wright *et al.* 1991). This model fixes the monopole and dipole using the high galactic latitude values, but allows for an adjustable amount of low latitude “normal” dust based on the 2-20 cm⁻¹ spectrum (rather than using DIRBE or FIRAS data at higher frequencies), so there is only one parameter at each pixel. The fit removes some of the 8-14 cm⁻¹ power but for dust with $T_d = 3.5$ K and power law emissivities $\propto \nu^\beta$ with β between 0 and 1.8, the fraction of the total very cold dust emission within the 8-14 cm⁻¹ band after the fit is

$$\frac{\int_8^{14} \left\{ \nu^\beta [B_\nu(T_d) - B_\nu(T_\circ)] - Gg(\nu) \right\} d\nu}{\int_0^\infty \nu^\beta [B_\nu(T_d) - B_\nu(T_\circ)] d\nu} \approx 0.3 \quad (5)$$

with

$$G = \frac{\sum_i \nu_i^\beta [B_{\nu_i}(T_d) - B_{\nu_i}(T_\circ)] g(\nu_i) / \sigma_i^2}{\sum_i g(\nu_i)^2 / \sigma_i^2} \quad (6)$$

using ν_i , $g(\nu_i)$ and σ_i from Mather *et al.* (1994). This reduces the expected excess to 0.03J W/m²/rad.

Converting the observed excess to a flux per radian requires multiplying by the range of latitude used, which is $\Delta b = 0.2$ rad. The result is

$$0.03J = (0.2 \text{ rad}) \times (6 \times 10^{-10} \text{ W/m}^2/\text{sr}) = 1.2 \times 10^{-11} \text{ W/m}^2/\text{rad} \quad (7)$$

so I obtain $J = 4 \times 10^{-9}$ W/m²/sr. The total power in the 2.7 K background is 10⁻⁶ W/m²/sr so this limit is 0.4% of the CMB energy. The interstellar radiation field (ISRF) given by Wright (1993) integrates to 2.5×10^{-6} W/m²/sr, which is 600 times higher than J . Thus if I assume that the CO clouds seen by Lequeux *et al.* are optically thick to starlight, and that the local ISRF decays outward with the normal exponential disk scale length of 3 kpc, then the predicted millimeter excess from the Galactic plane in the 8-14 cm⁻¹ range should be 600 times higher than it is. Even the heating provided by the diffuse extragalactic light (DEGL) would produce an 8-14 cm⁻¹ excess that is 10 times higher than the observed excess.

I conclude that CO clouds observed by Lequeux *et al.* can not be extremely optically thick objects hiding a large mass of very cold gas and dust. The observed number of clouds per unit $\cos b$ implies an absorption of the ISRF and DEGL that would produce a very large signal in the FIRAS Galactic plane observations, while only a small signal is seen. The low excitation temperature in CO is probably due to low density, giving $T_\circ \lesssim T_{ex} \ll T_{gas} \approx T_{dust}$. The clouds do absorb starlight, but the dust has a normal dust temperature, and the reradiation is already included in the FIRAS and DIRBE observations of the Galaxy.

DIRBE 3.5 Micron Flux

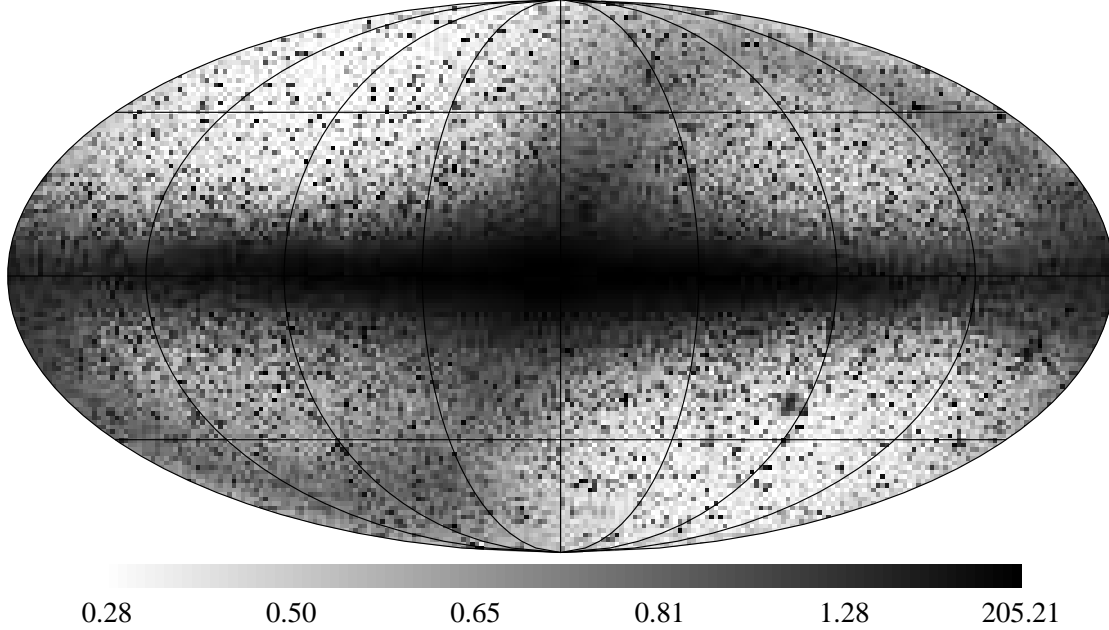


Fig. 4.— DIRBE flux in arbitrary linear units at $3.5 \mu\text{m}$. The darkest part of the sky is $\approx 10^5 \text{ Jy/sr}$ (Hauser 1994).

4. DIRBE Limits on a Brown Dwarf Halo

Adams & Walker (1990) and Daly & McLaughlin (1992) have computed the expected intensity from a brown dwarf Galactic halo. The expected flux is generally very low unless all of the halo density is made up of maximum mass brown dwarfs, $M = 0.08 M_\odot$. The halo mass density assumed by Adams & Walker is

$$\rho(r) = \rho_0 \frac{a^2}{a^2 + r^2} \quad (8)$$

with $a = 2 \text{ kpc}$ and $\rho_0 = 0.19 M_\odot/\text{pc}^3$ which gives a local density of $0.01 M_\odot/\text{pc}^3$. The mass column density to the galactic pole is $137 M_\odot/\text{pc}^2$ in this model. To convert this into a flux I need the mass and luminosity of a brown dwarf. I will assume $M = 0.05 M_\odot$, and the Burrows, Hubbard & Lunine (1989) luminosity of $10^{-6} L_\odot$ with an effective temperature of 632 K at an age of 10 Gyr. With an M/L of 50,000 the resulting intensity at the pole is $137 M_\odot/\text{pc}^2 / (4\pi M/L) = 2.2 \times 10^{-4} L_\odot/\text{pc}^2/\text{sr} = 10^{-10} \text{ W/m}^2/\text{sr}$. If I assume that the spectrum is a blackbody then the flux in individual bands is easy to find. The ratio $\nu F_\nu / F_{bol} = (15/\pi^4) x^4 / (e^x - 1)$ with $x = h\nu/kT$, which is 0.4 for $x = 6.5$ at $3.5 \mu\text{m}$ with $T = 632 \text{ K}$. Thus the intensity is 48 Jy/sr in this model. Since the total brightness at the South Ecliptic Pole is 175

kJy/sr, the prospects for detecting an 0.03% effect due to brown dwarfs are not very good.

Note, however, that the assumption of a blackbody spectrum is likely to be very bad. The spectrum of Jupiter shows very large features in the infrared. Warmer brown dwarfs with dusty atmospheres will have smoother spectra if the dust has a power law opacity $\kappa_\nu \propto \nu^\beta$. Since dust absorbs more at short wavelengths than at long wavelengths, the color temperature of a dusty brown dwarf will be smaller than the effective temperature, leading to an apparent emissivity $\epsilon = (T_{eff}/T_{color})^4$ that is close to 2. Since the emissivity is used to estimate the size of brown dwarfs, calculations based on blackbody emission will lead to sizes over-estimated by a factor of about 1.4. The lowered color temperature will further reduce the expected 3.5 μm intensity, and it also makes old cold brown dwarfs almost impossible to find in 2.2 μm surveys like those of Cowie *et al.* (1990). However, the individual brown dwarfs can easily be detected by the proposed Space InfraRed Telescope Facility (*SIRTF*). In a *SIRTF* 5' \times 5' field of view, the closest brown dwarf will be 66 pc away, and produce a flux of 3.7 μJy at 3.5 μm , but only 0.32 μJy at 2.2 μm . The lowered color temperature expected for dusty brown dwarfs will give fluxes of 2.2 μJy at 3.5 μm , but only 0.09 μJy at 2.2 μm . *SIRTF* will have a sensitivity of 0.02 μJy per pixel at 3.5 μm in a 2500 second observation and will easily detect many brown dwarfs per FOV at 3.5 μm , even though the integrated intensity is too small to be seen by DIRBE.

5. Summary

The observations by *COBE* of the CMBR show no evidence for non-gravitational forces producing large-scale structure. The gravitational forces implied by the DMR measurements of ΔT are sufficient to produce the observed large-scale structure only if most of the matter in the Universe responds freely to these gravitational forces before recombination, which requires non-baryonic dark matter. The baryonic dark matter cannot be very cold gas and dust associated with the CO absorption lines seen by Lequeux because it would produce too much millimeter wave emission from the Galactic plane. However, the dark baryons can easily be brown dwarfs which will escape detection by *COBE* and ground-based IR surveys but may well be seen by *SIRTF*.

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